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Probing the Impact of Stellar Duplicity on Planet Occurrence

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Abstract. The presence of a stellar companion closer than ~ 100 AU is likely to affect planet formation and evolution. Yet, the precise effects and their actual impact on planet occurrence are still debated. To bring observational constraints, we have conducted with VLT/NACO a systematic adaptive optics survey for close stellar companions to 130 solar-type stars with and without planets. In this paper we present observational and preliminary statistical results from this survey. Observational results reveal about 20 true companions, of which 4 are new companions to planet-host stars. As to preliminary statistical results, they suggest that circumstellar giant planets are less frequent in binaries closer than ~ 100 AU than around single stars, in possible agreement with the theoretical studies that predict a negative impact of stellar duplicity on giant planet formation in binaries closer than ~ 100 AU. These statistical results will need confirmation, however, as they are severely limited by small sample sizes.

1. Introduction

Nearby G-K dwarfs, which are first-choice targets for Doppler planet searches, are more often found in binaries or multiple systems than in isolation (e.g. Duquennoy & Mayor 1991; Halbwachs et al. 2003; Eggenberger et al. 2004). This observation, coupled with the growing evidence that many young binaries possess circumstellar or circumbinary disks susceptible of sustaining planet formation (Monin et al. 2007, and references therein), raises the question of the existence and frequency of planets in and around star systems of different types.

Over the past years, binaries have become increasingly interesting targets of planet searches and studies. Doppler surveys have shown that circumstellar giant planets exist not only in wide binaries, but also in the much closer spectroscopic binaries, implying that planets may be quite common in various types of binaries and hierarchical triples. Nonetheless, double stars closer than $2\text{--}6''$ present technical difficulties for Doppler planet searches (light contamination from the companions; Eggenberger & Udry (2007)). Most Doppler surveys avoid these systems accordingly, and the actual frequency of planets in binaries closer than ~ 200 AU is as yet unknown. Similarly, the existence of lower mass ($< 0.2 M_{\text{Jup}}$) circumstellar planets and the existence of circumbinary planets are

essentially unconstrained from the present observations. As a consequence, we will only consider circumstellar giant planets in this paper.

Theoretical studies have shown that the most sensitive issue regarding the occurrence of giant planets in binaries closer than ~ 100 AU seems to be whether or not these planets can form in the first place. Within the core accretion paradigm, planetesimal accretion can be significantly perturbed by the presence of a stellar companion closer than ~ 100 AU. Yet, these perturbations are usually not strong enough to fully halt accretion (Th  bault et al. 2004, 2006; Marzari et al. 2007). From this point of view, we thus expect giant planets to be present, though possibly less frequent, in several types of binaries closer than ~ 100 AU. Within the alternative disk instability model, the impact of stellar duplicity on disk fragmentation is more debated. According to Nelson (2000) and Mayer et al. (2005), disk fragmentation is generally suppressed by the presence of a stellar companion within 100 AU, while according to Boss (2006) disk fragmentation is promoted by the presence of a stellar companion with a periastron less than ~ 50 AU. If disk instability is a viable formation mechanism for giant planets, it is thus not clear yet whether we should expect more or less giant planets in intermediate binaries (50-100 AU) than around single stars. Nonetheless, the claim by Mayer et al. (2005) that stellar duplicity may inhibit giant planet formation via disk instability but not via core accretion in binaries separated by 60-100 AU, is particularly interesting and deserves further investigation. Indeed, if true, this statement would imply that planets residing in 60-100 AU binaries provide a unique means to probe the main formation mechanism for giant planets. In any case, quantifying the occurrence of giant planets in binaries closer than 200 AU, and studying how this occurrence varies with binary semimajor axis, may provide us with additional clues to better understand giant planet formation.

To quantify the impact of stellar duplicity on planet occurrence in binaries separated by ~ 35 -250 AU, and to test whether or not the occurrence of giant planets is reduced in binaries closer than ~ 100 AU, we are conducting a large-scale adaptive optics search for stellar companions to ~ 200 solar-type stars with and without planets (Eggenberger et al. 2007). To cover a substantial fraction of the sky, our main program is divided into two subprograms: a southern survey (130 stars) carried out with NAOS-CONICA (NACO) on the Very Large Telescope (VLT), and a northern survey (about 70 stars) carried out with PUEO on the Canada-France-Hawaii Telescope (CFHT). The NACO survey is now almost completed, while the PUEO survey is still halfway. In this paper we present observational and preliminary statistical results from the NACO survey.

2. The NACO survey

2.1. Overview

If the presence of a nearby stellar companion hinders planet formation or drastically reduces the potential stability zones, the frequency of planets in binaries closer than a given separation (modulo eccentricity and mass ratio) should be lower than the nominal frequency of planets around single stars. Alternatively, if the presence of a nearby stellar companion stimulates planet formation one way or another, planets should be more common in binaries with a specific range

of separations (again modulo eccentricity and mass ratio) than around single stars. Reversing these statements, studying the multiplicity of planet-host stars relative to that of similar stars but without planetary companions, may be a means of quantifying whether or not stellar duplicity impacts planet formation and/or evolution.

Since 2002, direct imaging has been used by several groups to detect stellar companions close to planet-host stars (Luhman & Jayawardhana 2002; Patience et al. 2002; Mugrauer et al. 2005, 2006; Chauvin et al. 2006). Yet, to push the investigation a step further and to study the impact of stellar duplicity on planet occurrence, one needs not only a sample of planet-host stars, but also a control sample of non-planet-bearing stars against which to compare the results. Such a control sample is also essential to take into account the selection effects against close binaries ($<2\text{--}6''$) in Doppler planet searches. The lack of a well-defined control sample is the major limitation that prevents the above-mentioned surveys to draw robust conclusions on the impact of stellar duplicity on planet occurrence. To overcome this limitation and to be as rigorous as possible, we included in our NACO survey both a subsample of planet-host stars and a control subsample of nearby field stars from our CORALIE planet search program showing no obvious evidence for planetary companions from radial-velocity measurements.

2.2. Sample, Observing Strategy and Observations

Our NACO survey relies on a sample of 57 planet-host stars, together with 73 control stars. The planet-host star subsample comprises nearby stars: (i) known to host a planet from Doppler surveys; (ii) visible from Paranal; and (iii) not appearing in previous, deep and relatively wide-field adaptive optics surveys, to avoid repeating existing observations. The control star subsample contains nearby stars: (i) belonging to the CORALIE planet search sample (Udry et al. 2000); (ii) with right ascension, declination, visual magnitude, color, and parallax as close as possible to the corresponding quantities of one of the planet-host stars; (iii) showing the least possible radial-velocity variations suggestive of the presence of a stellar or planetary companion. The larger number of control stars is intentional, as a few stars observed in other adaptive optics surveys will be added to the planet-host star subsample for the statistical analysis (see Sect. 3.).

The survey observing strategy consisted of taking a first image of each of our targets (planet-host and control stars) to detect companion candidates. To distinguish true companions from unrelated background stars, we relied on two-epoch astrometry. Since most of our targets are within 50 pc and have a proper motion above $0.1'' \text{ yr}^{-1}$, astrometric parameters of bound systems are indeed not expected to vary much over a few years, except for some orbital motion in the closest systems (Fig. 1, left). On the other hand, astrometric parameters of background objects without significant proper motion should vary according to the proper and parallactic motion of the primaries (Fig. 1, right). For relatively wide and bright companion candidates ($\rho > 10''$, $K < 14$), a preexisting astrometric epoch could usually be found in the 2MASS catalog (Skrutskie et al. 2006), meaning that only one NACO observation was needed to identify true companions. However, due to the high angular resolution of NACO, we could not rely on such preexisting data on a regular basis. To reject from the statis-

tics the numerous background stars we thus tried to reobserve the targets with companion candidates at a later epoch during the survey.

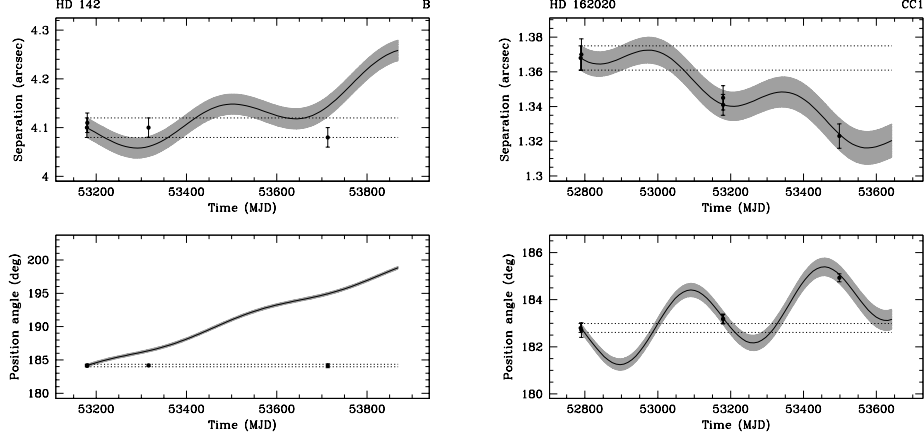


Figure 1. Examples of multiepoch astrometry from our NACO survey. Solid lines depict the evolution of angular separation and position angle for background objects with negligible proper motion. The gray zones are the related uncertainties. Dots represent our NACO observations and dotted lines depict the evolution expected for bound systems without significant orbital motion over the survey time span. The left panels show an example of true companion, while the right panels show an example of unrelated background star.

Our observations were spread over six different runs carried out between December 2002 and December 2005. For each target, we recorded unsaturated images in narrowband filter within the H or K band, the choice depending on atmospheric conditions. For an optimal sampling of the point spread function, the field of view was $13''$ for observations in the H band and $27''$ for observations in the K band. For targets within 50 pc, the $13''$ field of view translates into a projected separation range of a few AU (diffraction limit) to about 325 AU. Recalling the theoretical predictions mentioned in Sect. 1., this means that our survey probes a large fraction of the separation range where the presence of a stellar companion should affect giant planet formation (hence giant planet occurrence) to some degree.

2.3. Observational Results

Our data revealed 95 companion candidates in the vicinity of 33 targets. On the basis of two-epoch astrometry, we identified 19 true companions, 2 likely bound objects, and 34 background stars. The remaining 40 companion candidates (near 16 targets) either lack second-epoch measurements (most objects), or have inconclusive astrometric results due to insufficiently sensitive images at one epoch (few objects). The low likelihood of chance alignment shows that two of these 40 objects are very likely bound ($P < 0.1\%$), while ensemble statistics indicates that a few additional true companions might hide among these candidates. Follow-up observations are underway to identify these remaining bound systems.

Among planet-host stars, we discovered two very low mass companions to HD 65216, an early-M companion to HD 177830, and we resolved the previously known companion to HD 196050 into a close pair of M dwarfs. Besides these discoveries, our data confirm the bound nature of the companions to HD 142, HD 16141, and HD 46375. The remaining 11 true companions and the two likely bound objects all orbit control stars. These companions are late-K stars or M dwarfs, and have projected separations between 7 and 505 AU. We refer the reader to Eggenberger et al. (2007) for additional information on all these systems.

The typical sensitivity of our survey enabled us to detect stellar companions down to \sim M5 dwarfs at $0.2''$ and down to the L-dwarf domain above $0.65''$ (Fig. 2), providing us with a very complete census of the stellar multiplicity among our 130 targets. This observational material forms an unprecedented data set to study the impact of stellar duplicity on planet occurrence.

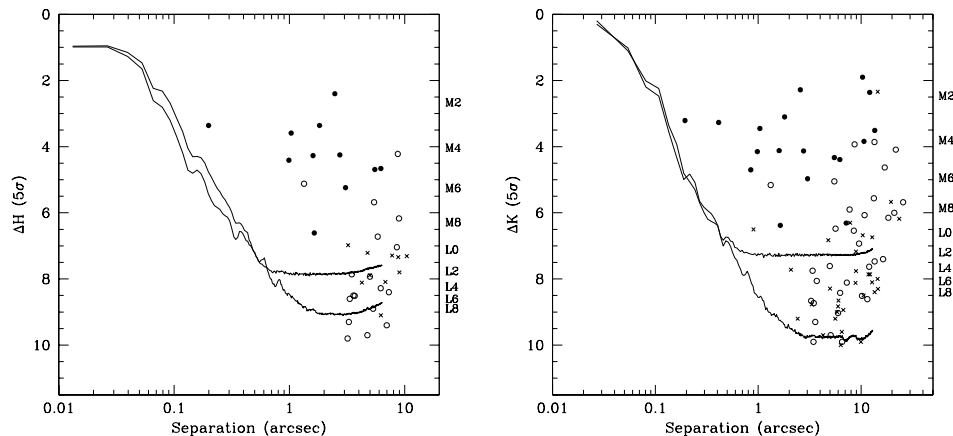


Figure 2. Sensitivity limits and detections from our NACO survey. Dots represent bound and likely bound companions, open circles represent unbound objects, and crosses denote companion candidates with only one astrometric epoch. Solid lines are the median detection limits obtained with the two different detectors of CONICA (a detector change occurred in the middle of our survey). Labels on the right-hand side of each plot show the relationship between magnitude (narrowband photometry) and spectral type for companions to a typical old K0 dwarf.

3. Preliminary Statistical Analysis

Although the inclusion of a well-defined control subsample reduces to their lowest value the corrections related to selection effects, some minor corrections and refinements in the definition of our two subsamples are still needed to properly quantify the impact of stellar duplicity on planet occurrence. A first debatable point is the exact definition of the control subsample, in particular regarding the non-planet-bearing status of these stars. Another issue is the relatively small

number of true companions (<20) that will likely render our statistical results quite sensitive to the exact definition of the two subsamples.

To get a first estimate of the impact of stellar duplicity on planet occurrence and to test the sensitivity of our results to the exact definition of each subsample, we performed a preliminary analysis based on two different sample redefinitions: (i) a loose redefinition where both subsamples were little modified except for an homogeneous cut-off at close separation ($\sim 0.7''$); (ii) a more stringent redefinition where both subsamples were limited in distance to 50 pc, and where control stars showing any type of radial-velocity variation were rejected. This additional selection was aimed at keeping in the control subsample as little potential planet-host stars as possible. Yet, by being too severe on this point we destroy the homogeneity in the selection of the control and planet-host subsamples and we may bias the results by rejecting more stars with close stellar companions from the control subsample than from the planet-host star subsample. Therefore, an optimum has to be found and the two cases presented here (i and ii) are intended to be some kind of lower and upper limits surrounding this optimum. Hereafter, the loosely redefined subsamples will be called “full” subsamples, while the more refined subsamples will be called “redefined”.

To both the full and redefined planet-host subsamples we added the stars observed by Patience et al. (2002) and Chauvin et al. (2006) when their sensitivity limits were better than ours in terms of contrast and field of view. We also assumed that the 40 companion candidates with only one astrometric epoch were unrelated stars, except for the two objects with a low likelihood of chance alignment ($P < 0.1\%$). Finally, for each filter (H and K) we defined a complete detection zone by using one of the worst sensitivity limit of the survey for separations up to $6.3''$. Angular separations were converted into projected separations (r), and then into mean semimajor axes (a), using the parallaxes of the primaries and the statistical relation $a = 1.26 r$ from Fischer & Marcy (1992).

To quantify the global impact of stellar duplicity on giant planet occurrence in binaries with mean semimajor axes between 35 and 250 AU, we computed the binary fraction for the four subsamples described above. The binary fraction of planet-host stars is $5.5 \pm 2.7\%$ (4/73) for the full subsample and $4.9 \pm 2.7\%$ (3/62) for the redefined subsample. For control stars, we obtain binary fractions of $13.7 \pm 4.2\%$ (9/66) and $17.4 \pm 5.2\%$ (9/52) for the full and redefined subsamples, respectively. These results translate into a difference in binary fraction (control – planet-host) of $8.2 \pm 5.0\%$ for the full subsample and of $12.5 \pm 5.9\%$ for the redefined one. Although the relative errors on these results are quite large due to the small number of available companions, both sample definitions yield a positive difference with a statistical significance of 1.6 - 2.1σ . In physical terms, this positive difference means that planets (mainly giant ones) are less frequent in binaries with mean semimajor axes between 35 and 250 AU than around single stars. In other words, stellar duplicity seems to negatively impact planet occurrence in binaries with mean semimajor axes between 35 and 250 AU.

To push the investigation a step further and to seek for a possible trend with mean semimajor axis, we computed the difference in binary fraction for a few bins (equally spaced in logarithmic scale) between 20 and 280 AU. The results for both the full and redefined subsamples are displayed on Fig. 3. These two

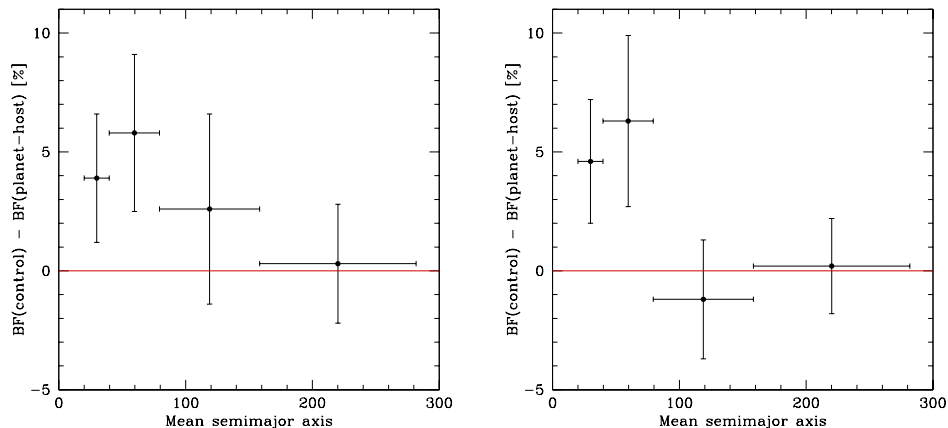


Figure 3. Difference (in per cent) between the binary fraction of control stars and the binary fraction of planet-host stars as a function of binary mean semimajor axis. The left plot is based on the redefined subsamples, while the right plot is based on the full subsamples.

plots show that the difference in binary fraction seems not spread uniformly over the semimajor axis range studied, but seems rather concentrated below ~ 100 AU. Taken at face value, this result is very appealing as it might corroborate the theoretical studies that predict a negative impact of stellar duplicity on planet formation in binaries closer than ~ 100 AU. Nonetheless, as just mentioned and as partly visible on Fig. 3, the small number of true companions available for the statistics severely limits our analysis. Larger samples will thus be needed to confirm the trends discussed here.

4. Concluding Remarks and Future Prospects

The preliminary statistical results presented here are quite encouraging and interesting as they might constitute the first observational evidence that circumstellar giant planets are less frequent in binaries closer than ~ 100 AU than around single stars. By adding about 70 stars to the statistics, the future results from our complementary survey with PUEO will make a valuable contribution to the analysis and will improve the statistical significance of the present results. It is worth recalling that the use of a well-defined control subsample ensures that the apparent lower frequency of planets in binaries closer than ~ 100 AU is not due to selection effects against close binaries in Doppler planet searches. In this respect, the preliminary statistical analysis presented here goes beyond what has been done so far, as the former analyses (Patience et al. 2002; Raghavan et al. 2006; Bonavita & Desidera 2007) could not correct their results for these selection effects.

One point on which all the observational studies agree, is that if stellar duplicity impacts the formation and/or survival of circumstellar giant planets in some types of binaries, this effect is not easy to identify and to quantify in prac-

tice. This conclusion may result from practical limitations in the surveys (small sample sizes, difficulty to correct for selection effects, practical impossibility to ensure that control stars are free from planets, ...), but it may alternatively have a more physical origin (not only binary semimajor axis but also eccentricity and mass ratio likely play a key role in determining the impact of stellar duplicity on planet formation and evolution, dynamical evolution may significantly alter the initial distributions and destroy the imprints of the formation process, ...). Recent Doppler searches for planets in spectroscopic binaries constitute another avenue to study the impact of stellar duplicity on giant planet occurrence. Since these programs typically target binaries closer than ~ 40 AU, their future results and conclusions will nicely complement those of the present imaging surveys. Our understanding of the impact of stellar duplicity on planet occurrence should thus significantly improve within the next years.

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